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FRACTURE DEFORMATION MEASUREMENTS IN THE LARGE BLOCK TEST

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ABSTRACT: Fracture deformations were measured in a 3m x 3m x 4.5m block of Topopah Spring tuff as part of a larger effort to characterize coupled thermal-hydrologic-mechanical-chemical processes in an isolated rock mass subjected to a one-dimensional thermal gradient. The fracture deformations were measured in three orthogonal directions at 17 points on the vertical faces of the block over a time span of 19 months. Eight fractures, including a major sub-horizontal fracture near the top of the block and five large, sub-vertical fractures, were selected for study. The data provide point measurements of apparent aperture change and slip motions parallel and perpendicular to the block faces. The fracture aperture and slip motions, though only a few tenths of a millimeter, form a significant portion of the total block deformation. The data reveal some fairly complex behaviors, such as non-uniform slip motions along individual fractures and sub-vertical fractures that sometimes open and close simultaneously at different elevations. Slip motions along sub-vertical fractures near the heater plane were relatively large and well correlated with temperature. The heating phase deformations were only partially recovered during cool-down. The fracture deformation data show that fractures deformed in conjunction with water movements and associated temperature fluctuations during the test. Simultaneous slip and aperture data also provide estimates of fracture dilation angle.

1. INTRODUCTION

The Large Block Test (LBT), conducted at Fran Ridge near Yucca Mountain, Nevada, comprises one phase of the field-scale thermal testing program of the Yucca Mountain Site Characterisation Project (YMP). A primary goal of the program is to improve understanding of coupled thermal-hydrologic-mechanical-chemical (THMC) processes in the near field environment of a potential high-level waste repository. The particular objective of the LBT was to monitor and characterise these processes in an isolated block of fractured rock subjected to a one-dimensional thermal gradient.

The Large Block consists of a 3m x 3m x 4.5m rectangular prism of Topopah Spring tuff exposed at an outcrop at Fran Ridge. One sub-horizontal and two sub-vertical fracture sets intersect the block. The sub-vertical fracture sets are approximately orthogonal, with a spacing of 0.25 to 1 m, and are oriented in the NE-SW and NW-SE directions. A major sub-horizontal fracture, located approximately 0.5 m below the top surface, dips eastward at a low angle. The sides of the block were insulated, and a heat exchange unit was attached to the top of the block to maintain a temperature of 60°C on the top surface throughout the test. The block was heated along a horizontal plane 2.75 m below the top surface for a period of 12 months, beginning Feb. 28, 1997 and ending March 10, 1998. Temperatures were measured at 0.1 m intervals in two vertical boreholes and on the outer surfaces of the block. A Multiple-Point Borehole Extensometer (MPBX) system measured the mechanical deformation of the block. The thermal, mechanical and hydrological responses of the Large Block were monitored during both the heating and cool-down phases of the test until Sept. 30, 1998 when the instrumentation was turned off. Large Block Test results are reported in Lin et al. [1]. Deformations of several major fractures were monitored as one component of the Large Block Test and are described here.

2. METHODS

Fracture deformations were measured with gauges consisting of two steel fixtures that straddle the fracture and three mutually orthogonal linear variable displacement transducers (LVDTs).

One fixture serves as the mounting block and the other as the reference block for the LVDTs. The gauges were mounted in T-shaped slots cut into the vertical faces of the block. The fracture gauges were mounted so that one LVDT (LVDT 1) measures aperture change, while the other two measure sliding in orthogonal directions, parallel (LVDT 2) and perpendicular (LVDT 3) to the face. These are approximate measures of in-plane and normal fracture deformations as the chosen fractures intersect the vertical faces at high angles. Thus, the measurements can provide estimates of fracture deformation parameters, such as dilation with sliding. Approximate gauge locations are shown for each face in Figure 1 and coordinates are given in Table 1.

The fracture monitors were installed on the four vertical faces of the block as follows:

- On the north face, gauge NF5 was mounted along Fracture 1, a large sub-horizontal near the top of the block, and three gauges (NF2, NF3, and NF4) were mounted in a sub-vertical fracture zone, containing Fracture 12 and Fracture 13, near the center of the north face (Figure 1a).
- On the east face, three gauges (EF2, EF3, and EF4) were mounted along a prominent vertical fracture (Fracture 3) near the center of the face, and one gauge (EF1) was mounted on Fracture 1 (Figure 1b).
- On the south face, three fractures were monitored (Figure 1c). Gauges SF1 and SF2 were mounted on a major sub-vertical fracture (Fracture 17), gauge SF3 was mounted on a sub-horizontal fracture in the lower, southwest portion of the block (Fracture 281) and gauge SF-4 monitored Fracture 1 near the top of the block.
- On the west face, gauge WF5 was mounted along Fracture 1, three gauges (WF1, WF2, and WF4) were mounted along a sub-vertical fracture (Fracture 34) near the northwest edge, and gauge WF3 was mounted along a sub-horizontal fracture (Fracture 452) near the lower, northwest corner (Figure 1d). Data were not collected for several gauges on the west face during the first twenty days of the test due to an instrumentation problem. Displacement values were set to zero at Day 20 for these transducers.

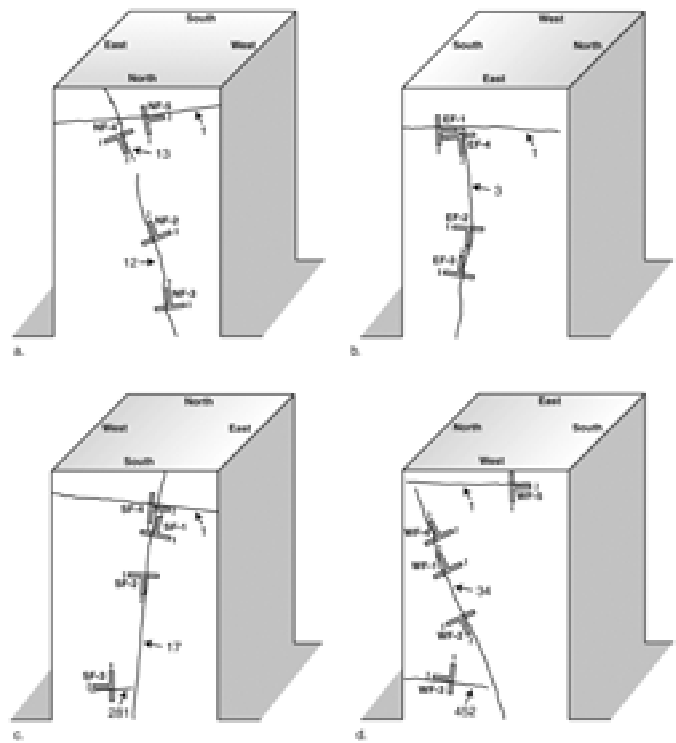

Fig. 1. Fracture deformation gauge locations and fracture identification numbers. Not to scale. a.) north face. b.) east face. c.) south face. d.) west face.

Aperture changes were taken directly from the measured LVDT 1 displacements. Slip was computed as the vector sum of the two perpendicular displacements (LVDT 2 and LVDT 3) measured approximately parallel to the fracture plane. Data from several of the fracture deformation gauges show diurnal variations due to ambient temperature changes and high frequency noise. Daily averages were computed for each displacement component and used to compute cumulative slip for each fracture deformation gauge. Aperture changes were plotted against slip for each fracture deformation gauge, and ordinary least squares was used to regress straight lines through the linear portions of these data. Apparent fracture dilation angles were calculated as the arctangents of the slopes obtained from the linear regression fits.

3. RESULTS

3.1. Aperture Changes

Aperture changes were recorded for all monitored fractures. The largest aperture changes, between 0.3 and 0.4 mm, were recorded along vertical fractures near the heater plane and along Fracture 1, the large sub-horizontal fracture near the top of the block. The smallest aperture changes, mostly under 0.05-mm, were recorded along vertical fractures near the top and bottom of the block and along the two small, sub-horizontal fractures near the base of the block. The vertical fractures exhibit both positive (opening) and negative (closing) aperture changes. The opening motions are concentrated in hotter portion of the block, within 0.85 m of the heater plane (Figure 2a), and the closing motions are concentrated in the cooler regions toward the top and bottom (Figure 2b).

The measured aperture changes for the vertical fractures are well correlated with each other near the heater plane throughout the heating portion of the test (375 days). Most of the opening motion occurred in the first 50 days when temperatures were rising rapidly near the heater plane. Abrupt closing motion at about 125 days, followed by gradual reopening, was observed for all five gauges near the heater plane (Figure 2a). The sudden closure at 125 days coincides with a rise in temperature above boiling near the heater plane (see Figures 3 and 4) and may indicate a loss of liquid water in the fractures. Aperture changes are well correlated at three of the gauge locations during cool-down (Figure 2a). Two of these, EF-2 and EF-3, monitor the same fracture and are approximately 0.5 m apart. The third gauge, SF-2, is located on the south face and at somewhat greater elevation. These gauges show abrupt closing motions at the beginning of the cool-down, followed by gradual reopening (Figure 2a). The gradual reopening motions may indicate a reintroduction of liquid water into the fractures at these locations as the rock cooled below boiling. The other two gauges record distinctly different behavior. On the west face gauge WF-2 gradually closed throughout cool-down. On the north face, gauge NF-2 abruptly opened 0.15 mm at the start of cool-down.

Aperture changes along vertical fractures were generally gradual away from the heater plane, except at 125 days when two gauges, WF-1 and NF-3, indicate sudden closure (Figure 2b). Gauge WF-1 is located along Fracture 34 at 0.90 m above the heater plane and gauge NF-3 is located on Fracture 12 at 1.19 m below the heater plane. Both fractures closed abruptly in the vicinity of the heater plane and apparently these locations also lost liquid water, or were affected by whatever mechanism induced the sudden closure. Three gauges were installed along vertical fractures near the intersection with Fracture 1, and each shows rather different behavior. The aperture of Fracture 3 remained almost constant at gauge EF-4 throughout the test. In contrast, Fracture 13 closed continually at gauge NF-4 throughout the heating phase of the test and by more than any other monitored fracture. At the location of gauge SF-1, Fracture 17 shows intermediate behavior: it closed moderately during heating, then reopened during cool-down. The other gauges, NF-3, WF-1 and WF-4, reached maximum closure around Day 150, then remained essentially unchanged in aperture throughout the remainder of the test, including the cool-down period.

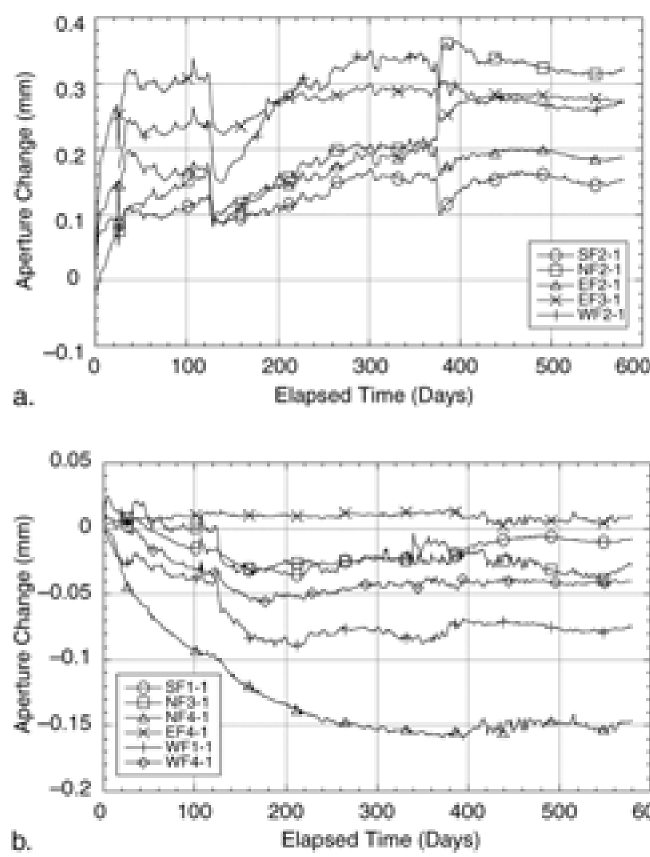

Fig. 2. Aperture change on vertical fractures at a.) locations within 0.85 m of the heater plane. b.) locations more than 0.85 m above or below the heater plane.

Individual vertical fractures opened and closed simultaneously at different levels. On the west face Fracture 34 opened over 0.3 mm at 0.10-m above the heater plane (gauge WF-2) and closed at locations 1.5 m above (gauge WF-4) and 0.90 m below (gauge WF-1) the heater plane (Figure 3). Similarly, Fracture 12 on the north face opened over 0.3 mm at 0.05 m above the heater plane (gauge NF-2) and closed about 0.05 mm at the gauge NF-3 location 1.19 m below the heater plane (Table 2). On the south face Fracture 17 opened a little under 0.2 mm at a location 0.83 m above the heater plane (gauge SF-2) and closed about 0.05 mm at a location 1.6 m above the heater plane (gauge SF-1). Fracture 3 opened 0.2 mm at gauge EF-2, located 0.1 m above the heater plane, and 0.35 mm at gauge EF-3, 0.6 m below the heater plane, but remained essentially unchanged in aperture throughout the test at gauge EF-4, near the top of the block.

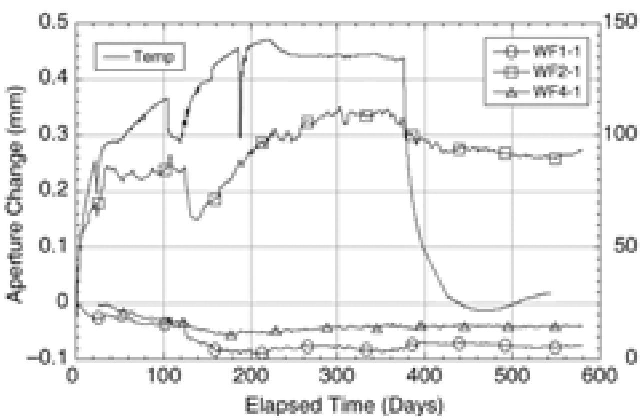

Fig. 3. Aperture changes on Fracture 34 and heater plane temperature history from vertical borehole TT-1. Fracture deformation gauges WF-4, WF-1 and WF-2 are located 1.54 m, 0.90 m and 0.10 m above the heater plane, respectively.

3.2. *Slip Motions*

Outward slip motions along three vertical fractures at points near the heater plane were well correlated with heater plane temperature, as measured in borehole TT-2 near the east face (Figure 4). Opposing fracture surfaces slipped past each other as the block expanded and contracted during the test. On the north face, gauge NF-2 reveals up to 0.55 mm of slip displacement, representing outward motion of the east wall of Fracture 12 relative the west wall. The outward slip displacement is more than twice the aperture change recorded during the heating phase of the test by the same gauge. On the south and east faces, gauges SF-2 and EF-2 show smaller outward slip motions, but ones which are still well correlated with the heater plane temperature. The NF-2 displacement record follows the temperature history particularly closely. Approximately 0.4 mm of displacement was recorded by Gauge NF-2 during the first 70 days of the heating, during which the rock temperature near the heater plane rose to the boiling point. The recorded temperatures remained essentially constant for about 60 days, then rose rapidly after the rock dried out at the level of the heater plane. The slip displacement records for the three gauges show the same pattern. Maximum outward displacements were reached at about 220 days coinciding with the peak heater plane temperature. The power supply to the heaters was reduced at that time, resulting in a gradual drop in temperature and a reversal of the slip motions. The power supply to the heaters was shut off on Day 375, and was followed by a rapid drop in temperature and rapid slip displacements. Residual slip displacements at the end of the test were about 0.05 mm at the locations of gauges SF-2 and EF-2 and about 0.1 mm at gauge NF-2.

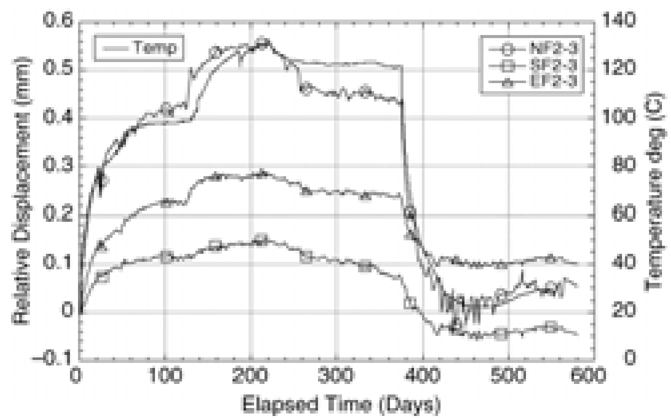

Fig. 4. Relative outward (perpendicular to the block face) displacements near the heater plane and heater plane temperatures from vertical borehole TT-2, located near the east face. Gauges NF-2, EF-2 and SF-2 are located 0.05, 0.11 and 0.83 m above the heater plane, respectively.

Slip motions were measured on all four faces of the block along Fracture 1, the major eastward dipping discontinuity near the top of the block. The east-west slip components (Figure 5) reveal that the top of the block moved eastward relative to the base throughout the heating phase of the test, corresponding to normal fault motion. The north-south slip components (not shown) are smaller than

0.1 mm. Much of the eastward slip occurred in the first 100 days of heating, when temperatures were rising rapidly in the block. The slip motions reversed on Day 375 when cool-down began. Most of the relative westward motion of the rock above the fracture plane occurred during the first 50 days of cooling. Except for gauge WF-5, the westward displacements on cool-down are under 0.1 mm, so that the final, residual displacements are eastward for three of four faces.

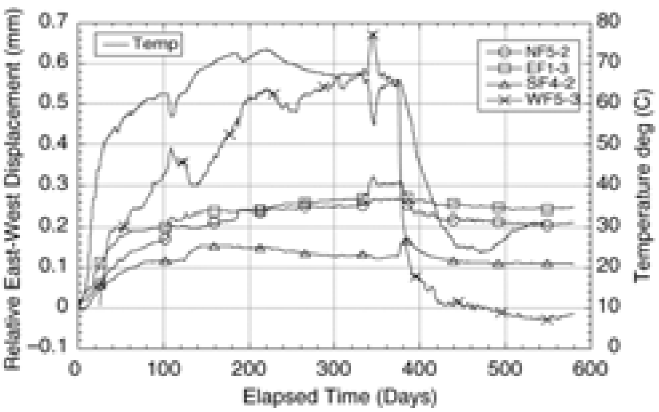

Fig. 5. Relative east-west displacement along Fracture 1, the large sub-horizontal fracture near the top of the block. Eastward displacements of the upper, hanging wall are plotted as positive. Temperatures were measured in borehole TT-2 at the approximate level of Fracture 1.

The east-west slip motions shown in Figure 5 indicate that the rock above Fracture 1 did not move as a single, intact unit, but that the western portion was much more mobile than the rest. Both the largest eastward and westward displacements were recorded by gauge WF-5 on the west face. Gauge WF-5 recorded approximately 0.3 mm of relative eastward motion during the first 100 days, during which the other gauges recorded between 0.1 and 0.2 mm of movement. An additional 0.3 mm of eastward displacement were recorded by gauge WF-5 between Days 100 and 330, during which the other three gauges show at most 0.1 mm of eastward movement. Around Day 340 gauge WF-5 recorded an additional, temporary 0.1 mm of eastward displacement in response to a short-lived thermal hydrological event, to which the other gauges show a smaller response. The total eastward displacement for WF-5 of just under 0.7 mm is more than one quarter of the approximately 2.5 mm east-west deformation recorded over a 2.6 m baseline by an MPBX system near the top of the block [1]. The WF-5 displacements differ from those of the other three gauges along Fracture 1 in that they were fully recovered on cool-down. The other three gauges show relative eastward displacements during heating of 0.15 to 0.3 mm and only partial recovery, of about 0.05 mm each, on cool-down.

Maximum and residual slip motions given in Table 2 indicate that the fractures that underwent the most slip during heating, also experienced more recovery on cool-down. Among the largest were Fracture 3 (gauge EF-3) and Fracture 12 (gauge NF-2) each of which experienced about 0.6 mm of slip. About 50-60% of this slip was recovered for both fractures during cool-down. In contrast, many of the fracture gauges that recorded maximum slips between 0.1 and 0.2 mm show little or no recovery. The correlation between maximum slip, which was generally experienced during the heating phase, and the amount of recovered slip, may be related to the temperature history of the block. Along vertical fractures, the gauges experiencing the most slip, and the most recovery, were located near the heater plane, where the largest thermal expansion and contraction deformations would be expected.

3.3. Dilation Angles

A linear relation between slip and aperture change was observed at various times for most of the fracture deformation gauges. Apparent dilation angles were obtained from the slopes of regression lines fit to the linear portions of the aperture change versus slip data. The time intervals and slip ranges over which linear relationships were observed varied widely, from as few as 12 days to over 350 days, and from under 0.01 mm to 0.7 mm. At least one estimate of apparent dilation angle was obtained for each monitored fracture (Table 3). The estimated dilation angles vary from 17° to 60°, with half of the values below 35°. Several of the lower dilation angles were obtained from data sets having relatively long ranges of slip. Five of the six lowest dilation angles were obtained from data sets having slip ranges over 0.10 mm, whereas three of the four highest dilation angles were obtained over slip ranges of under 0.01 mm. A weighted average of all the dilation angles, using the slip ranges as weights, yields a dilation angle of 30°. Data from gauge WF-5 on Fracture 1 exhibited a particularly long-lived linear relationship between slip and aperture change (Figure 6). The time interval lasts from Day 26 to Day 381, about a week into cool-down. The slip range of 0.7 mm matches the entire range of relative east-west displacement observed for this gauge (Figure 6). The regression fit is tight and yields an apparent dilation angle of 27°.

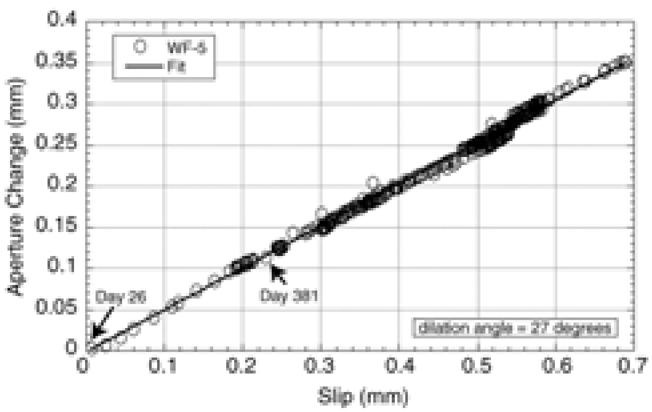

Fig. 6. Aperture change versus slip and linear regression fit for Fracture 1 displacements measured by gauge WF-5 over an interval of approximately one year. Slip was predominantly in the east-west direction.

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4. CONCLUSIONS

Fracture aperture and slip motions, though only a few tenths of a millimeter, form a significant portion of the total deformation experienced by the Large Block. The measurements reveal a variety of behaviors, including simultaneous opening and closing motions at different elevations along vertical fractures. These opened in the hotter portion of the block, near the heater plane, and closed in the cooler, upper and lower regions during the heating phase of the test. Slip motions along vertical fractures near the heater plane were relatively large and well correlated with temperature. Fracture 1, the large sub-horizontal fracture near the top of the block, experienced normal fault motion during the heating phase and reverse fault motion during the cooling phase of the test. Fractures sometimes deformed in conjunction with water movements and associated temperature fluctuations during the test. East-west slip motions along Fracture 1 are well correlated with temperature excursions at 105 and 340 days. Many of the heating phase deformations were only partially recovered during cool-down, but those fractures experiencing greater slip during heating generally experienced more complete recovery on cool-down. Simultaneous slip and aperture data provided estimates of apparent fracture dilation angle.